Quench Protection of High Field Nb_3Sn Magnets for Particle Accelerators

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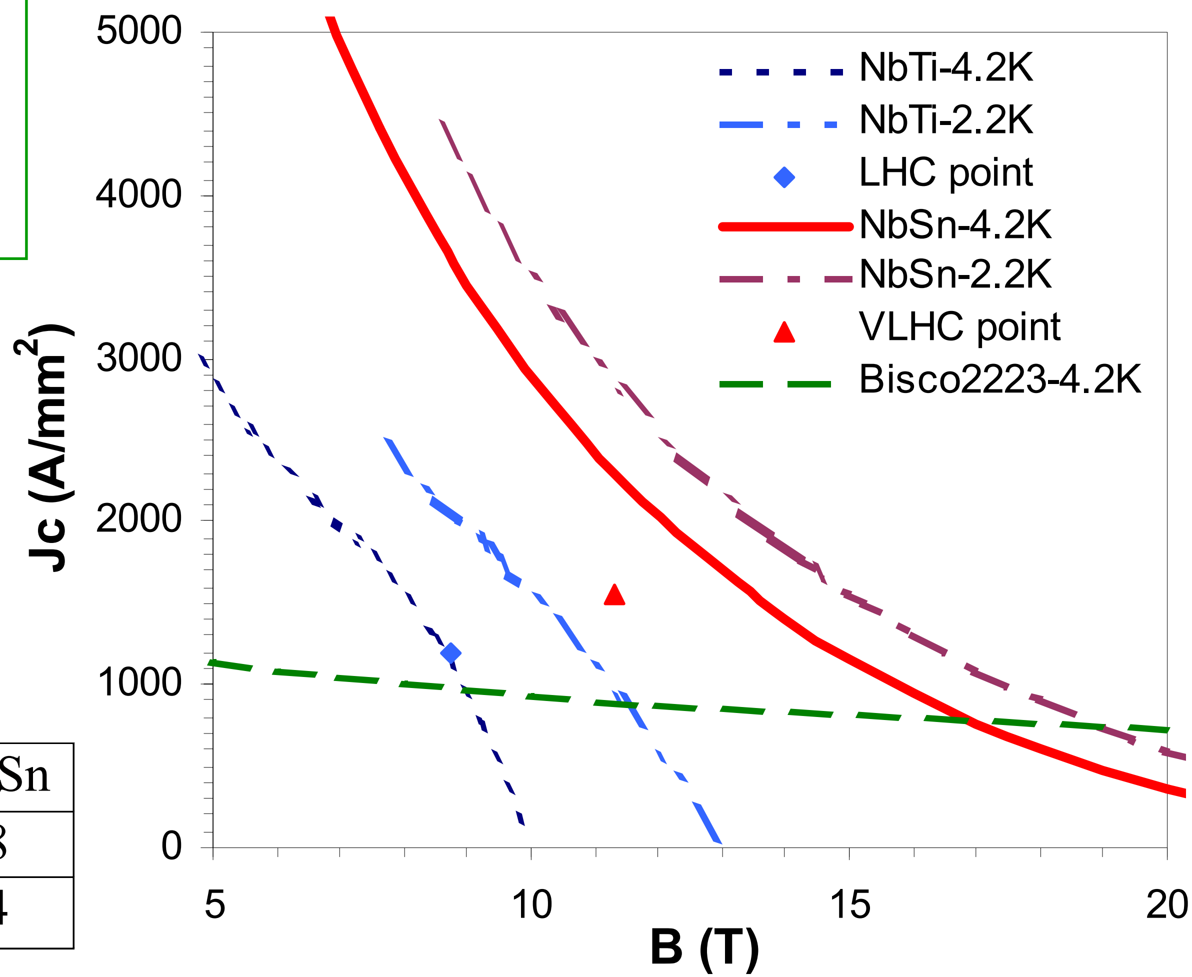
Outline

- Nb$_3$Sn main properties
  - SC properties
  - Quench characteristics & Dangers
  - Strain dependence
- Quench protection
  - Methods
  - Hot Spot temperature: MIIts
  - voltage
- Quench simulations and parametric studies
  - Generic HFM quench study: trends varying field, current …
  - VLHC/FNAL magnets
  - LHC-2 quad
- Thermal stress
  - Experiments
    - Cables
    - racetrack
  - Simulations and FE analysis

SC material: Nb_3Sn

NbTi :
- Tevatron: 4.5 T at LHe
- HERA: 5.5 T at LHe
- LHC: 8.4 T at HeII

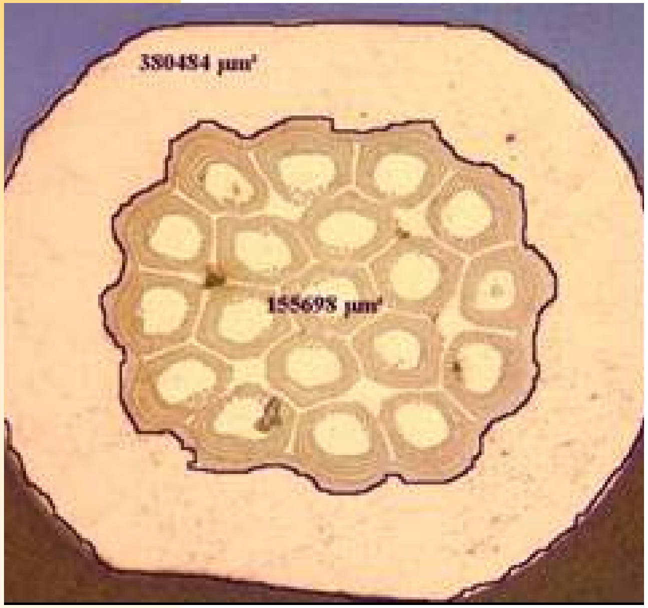


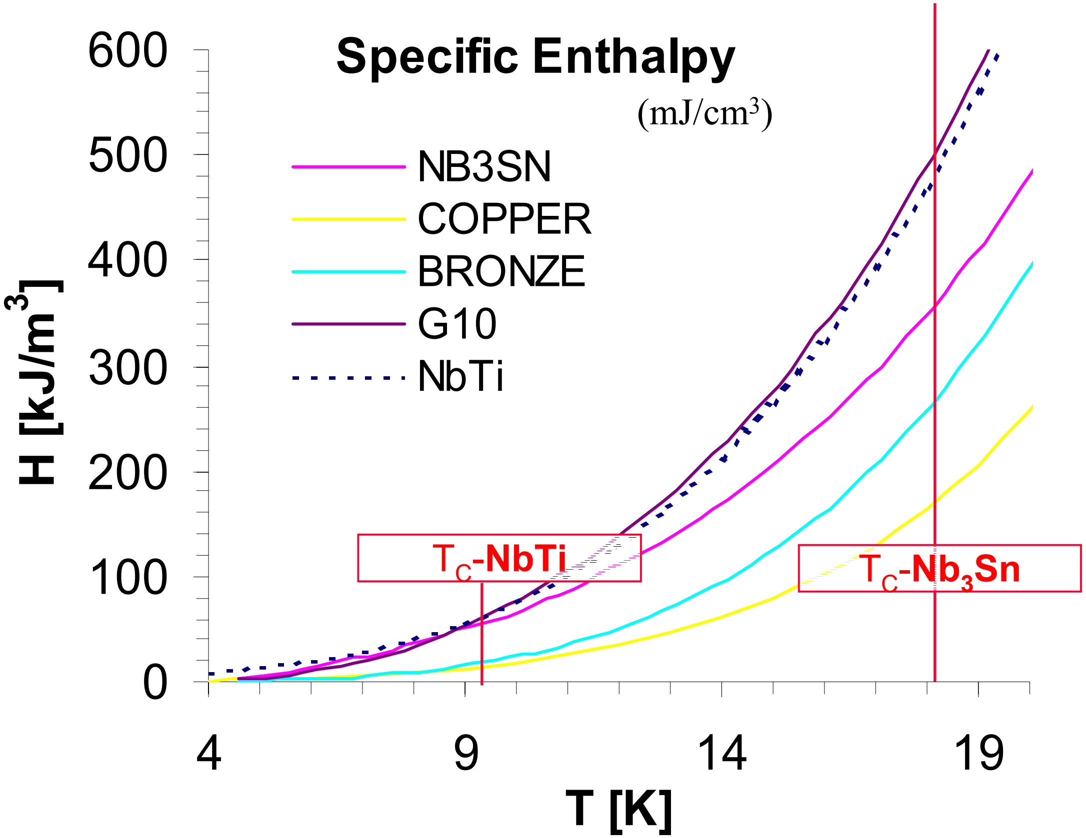
	NbTi	Nb_3Sn
T_c (K)	9.4	18
B_c(4.2K) (T)	11	24

Stability of Nb_3Sn

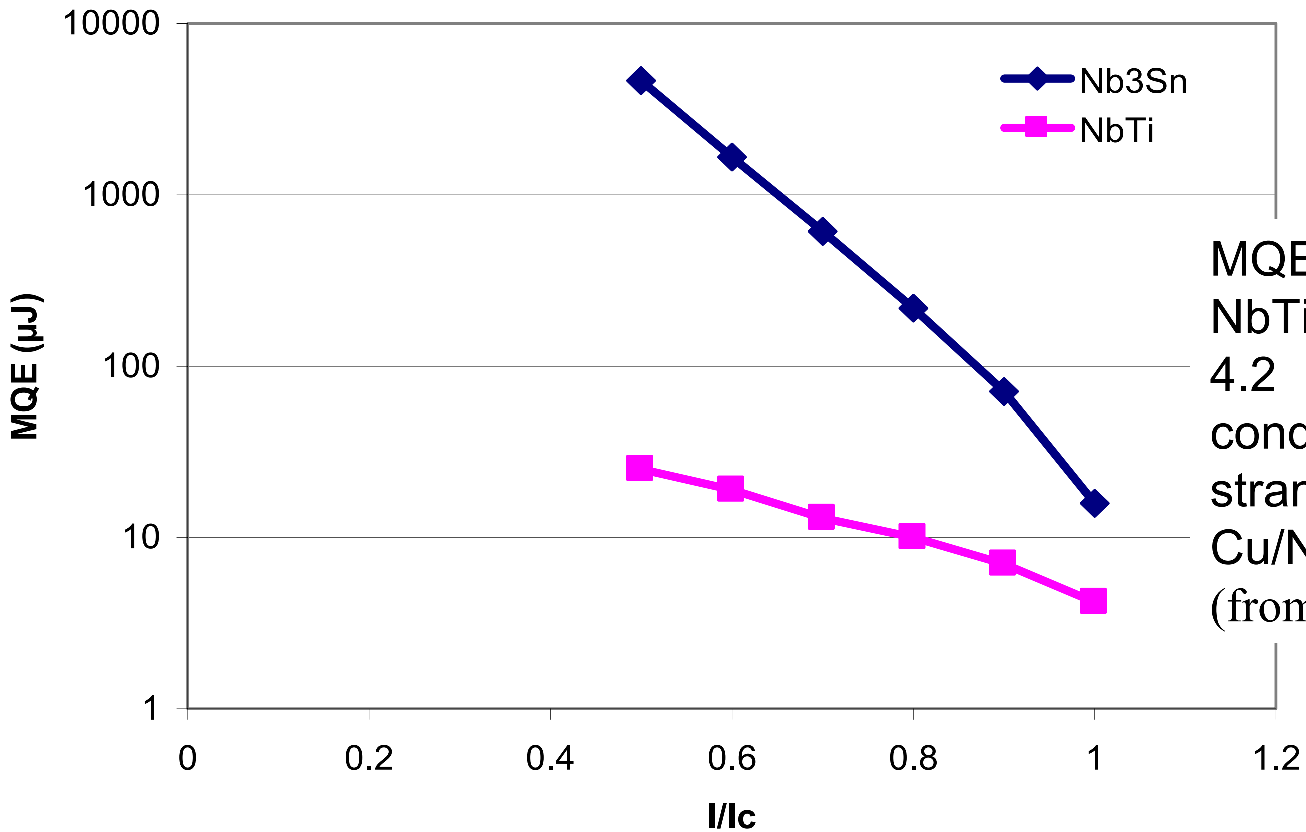
Nb3sn should be more stable than NbTi: $\Delta T = \Delta E / c_P$

Heat capacity at low temperature ($T \ll T_{Debye}$): $c_P \sim T^3$





Stability of Nb_3Sn



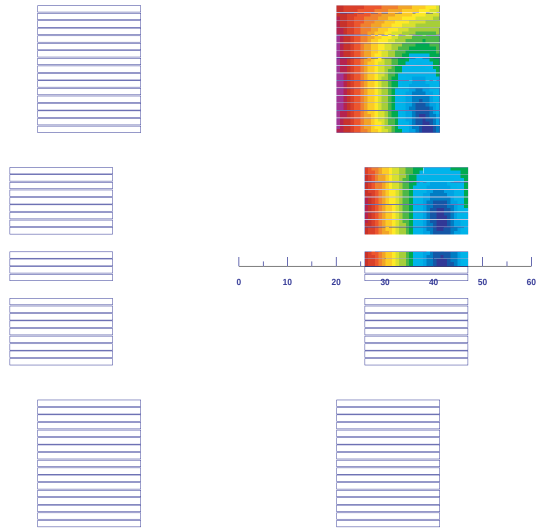
MQE of Nb_3Sn and NbTi strands at 8 T, 4.2 K in "adiabatic" conditions;
strand diam. : 1 mm, Cu/NCu=1.6
(from P. Bauer)

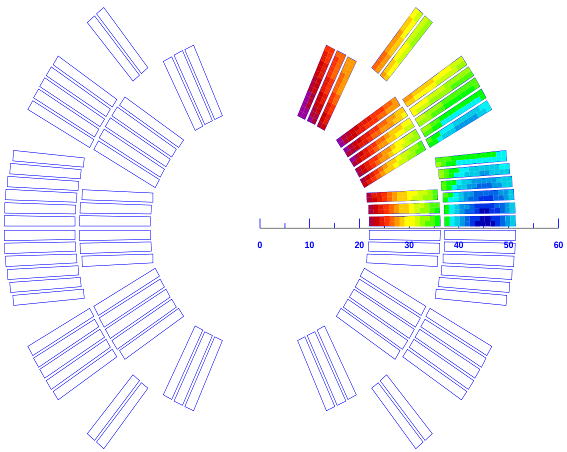
A **movement** of the order of **1 μm** of a wire L= 5 mm, ∅=1mm (Volume ≅ 4 mm³), in a 10 T field, dissipates

$\Delta E = J\,B\,\delta\,Vol \approx 2\cdot10^{9}\ 10\ 10^{-6}\ 4\cdot10^{-9} =$ **80 μJ** ➔ **I/Ic<0.9**

High Field magnets

Magnet parameters	**VLHC CC**	**VLHC cosθ**	**LHC HGQ-2**	**LHC cosθ**
Bore Field/Peak Field (T)	10/11.3	10/10.5	10/10.3	8.3
Operating Current (kA)	**23.5**	**21.3**	14.5	11.8
Inductance (mH/m)	3	2.1	4.7	7.4
Stored Energy (kJ/m)	**828**	485	489	490
Length (m)	16	16	6	14.5
Cable Cross Section (mm^2)	23.1	22.5	24.3	25.5





The quench

Basic process of the quench: conversion of stored e.m. energy into heat

The magnitude of quench process is mainly given by :

	VLHC CC	**VLHC** **cosθ**	**LHC** cosθ
J_{CU} (A/mm^2)	1990	1730	710
QI(300K) ($M\ A^2\ s$)	40	50	71
QI(@30ms) ($M\ A^2\ s$)	14	17	4

With no active protection:

$\rho J_{Cu}^2 \cong 6\ 10^{-10}\Omega m \cdot 10^9 (A/m^2)^2 =$ **600 MW/m³**

Dangers

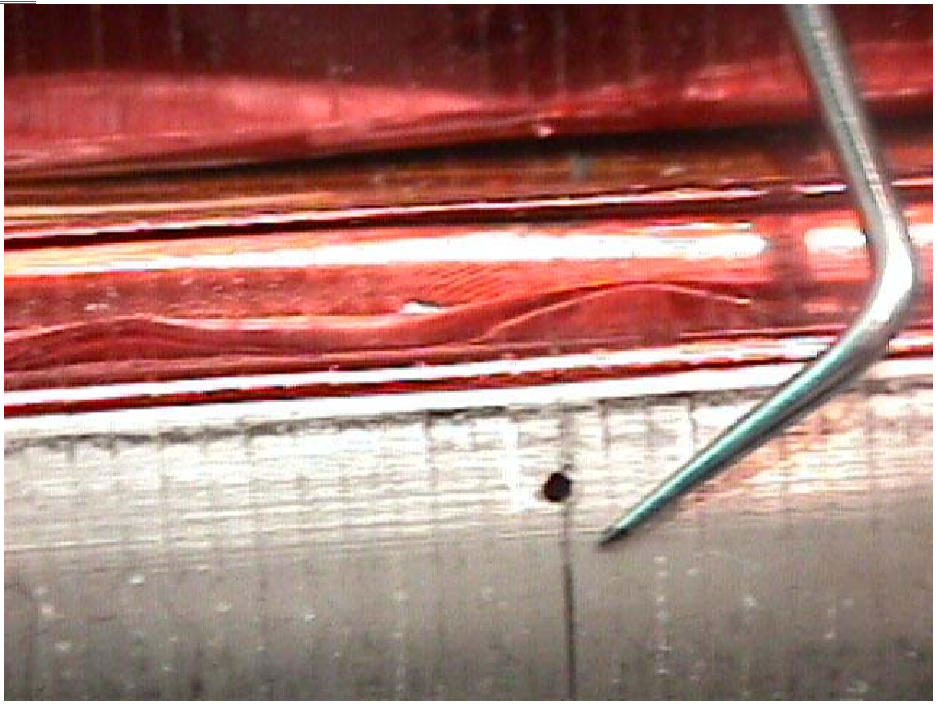
- Excessive **temperature** damages insulation
- Excessive **temperature gradients** creates great **stresses** => critical current degradation (Nb_3Sn)
- **Voltage** to ground and inside winding => short circuit and arching

  (Helium gas in straight field has very low breakdown voltage)
- Helium blow off after quench => problem of **pressure**, especially for strings of magnets inside a single cryostat

Helium Blow off after 8 T Nb_3Sn magnet quench -NHMFL

Protection failures – Voltage

LHC dipole: Short circuit



Damage caused by a short circuit developed during a quench in a LHC dipole protype

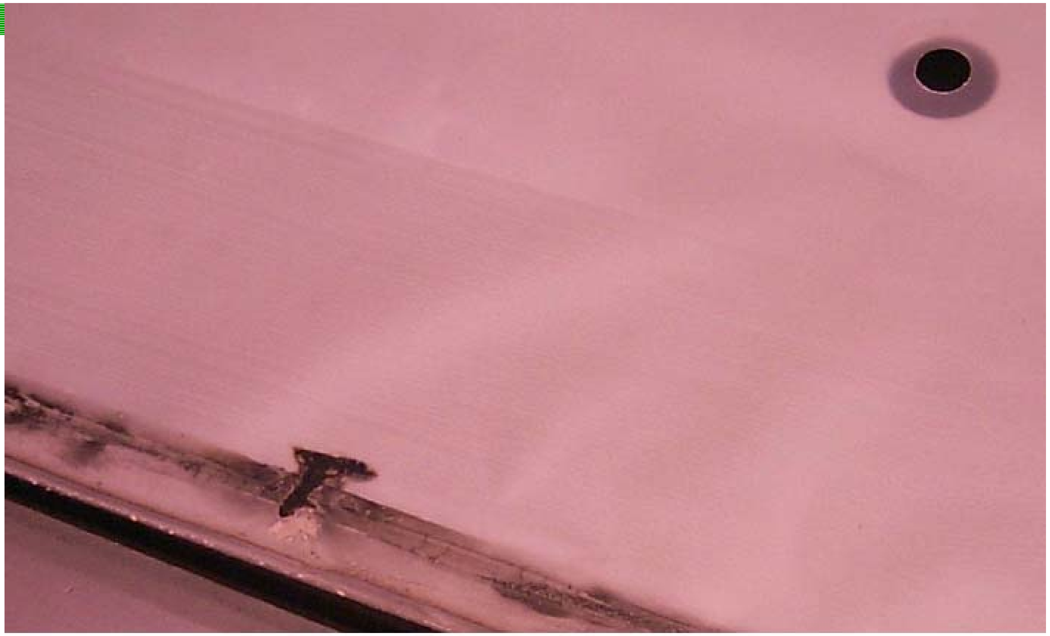
(From L. Rossi - academic training – Cern)

Quench protection failure

RD3 damage

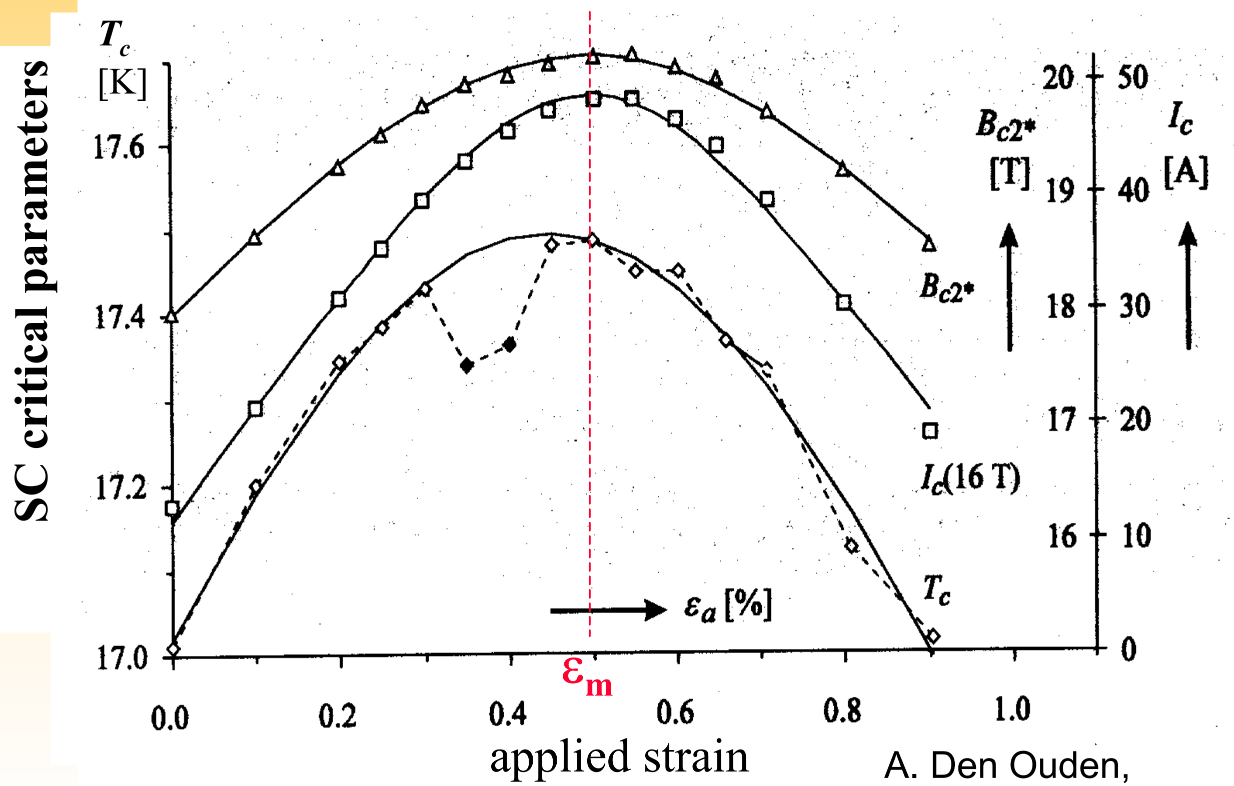
Quench protection failure

RD3 damage



Nb_3Sn strain dependence

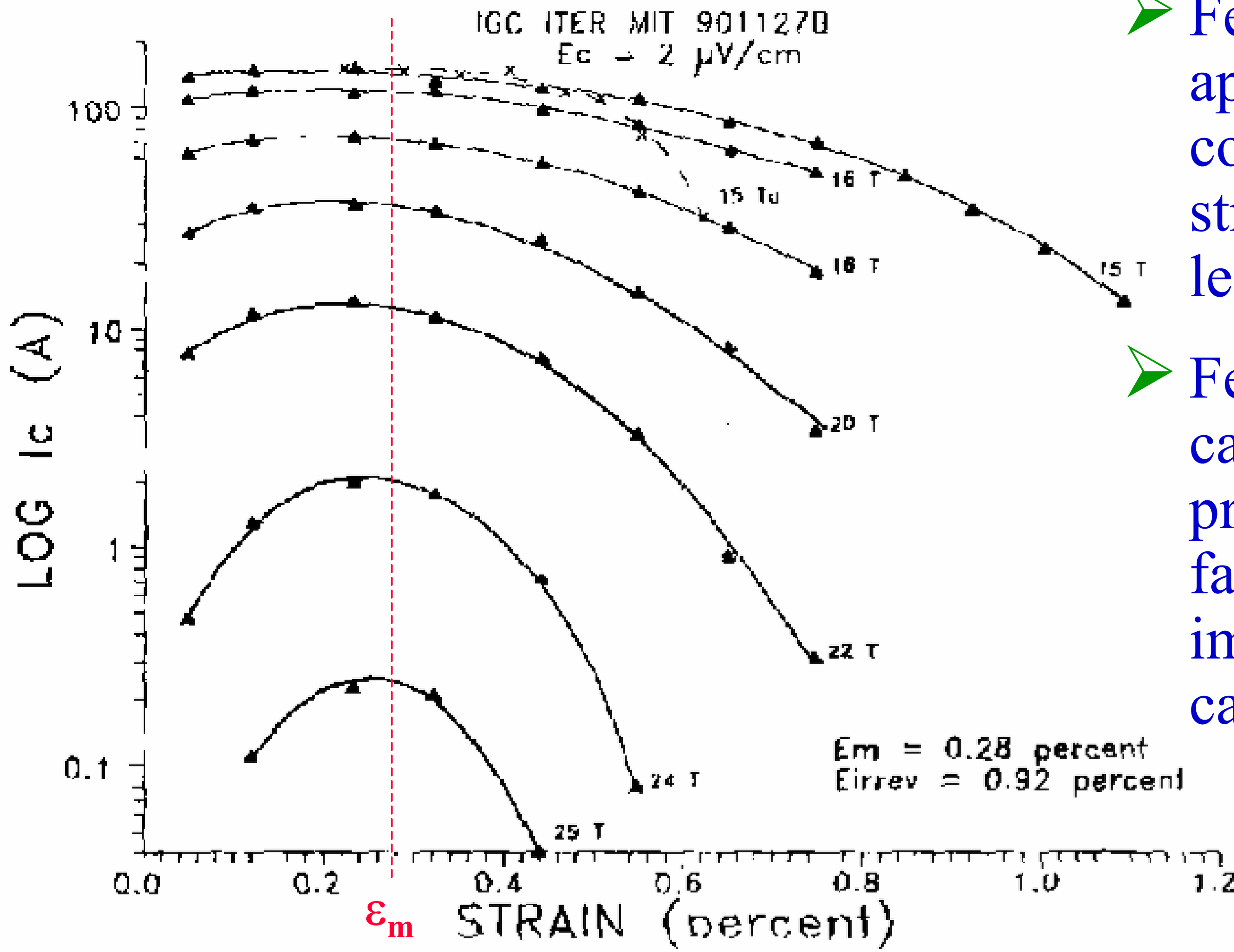
- Bare Nb_3Sn filaments break at ~**0.2%** uniaxial tensile strain.
- In composites, the Nb_3Sn filaments are under **compression** at zero applied strain (**ε_a=0**) due to thermal contraction differences.



A. Den Ouden, Univ. of Twente

- I_c max for $\varepsilon_a=\varepsilon_m$: intrinsic strain minimum
- Irreversible I_c degradation starts at higher tensile ε_a

Nb_3Sn I_c strain dependence



- Few data for applied compressive strain, generally less critical
- Few studies on cables: max. pressure on broad face for impregnated cables ~150 MPa

Nb_3Sn quench degradation

Intrinsic strain factors :

- thermal pre-compression
- Cable structure (twist, transposition, keystone angle, etc.)
- winding after reaction (~ 0.18 % for the CC design)
- any applied strain, as pre-stress and Lorentz forces.
- **strain induced by anisotropic thermal expansion during the quench process**

Quench protection steps

1. Quench detection

   fast but reliable

1. Current disconnection

   switch or diode

2. Extract stored energy

   significant for small magnets

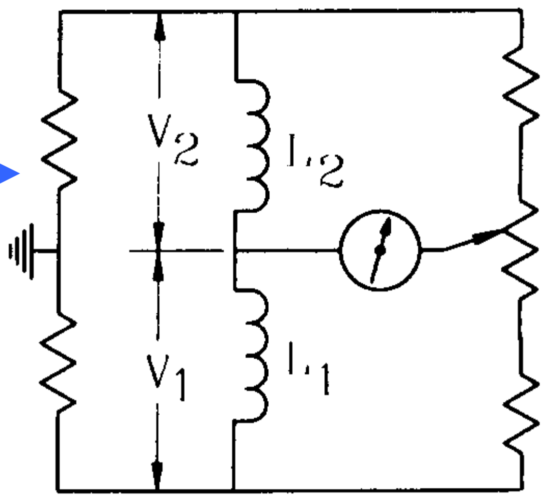
3. Spread energy in the coil

   reduces peak T and V

1- Quench detection:

Most used for accelerator magnets:

– Voltage taps detecting resistive growth
– Noise rejection with bridge circuit
– Signal processing (software)



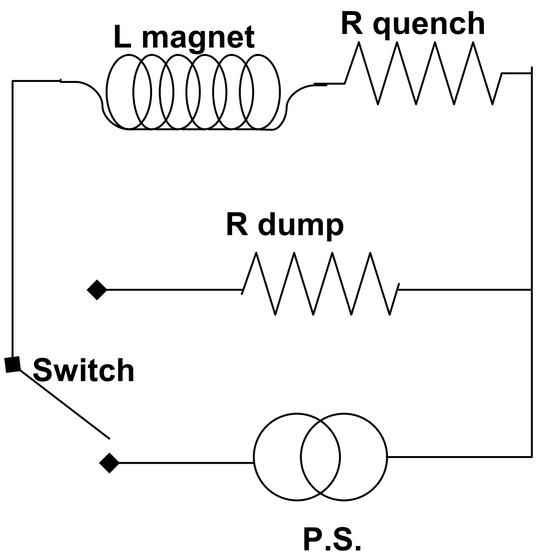
Others techniques:

– Quench antenna (inductive signals)

– Temperature sensors (fiber optics) ~1 s

– Microphones

2- Current disconnection &
3- Stored energy extraction



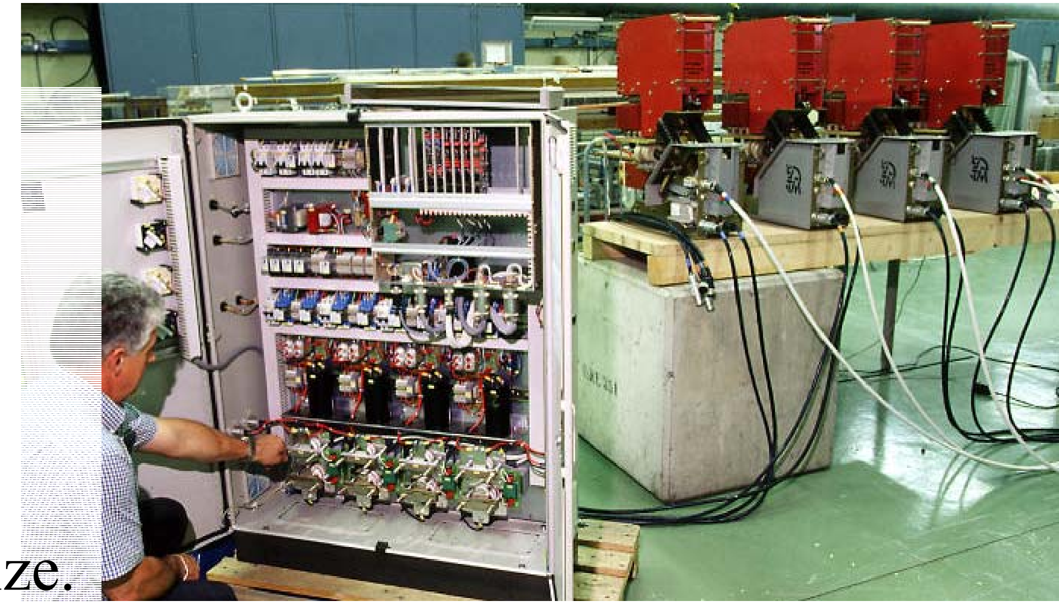
– Switch
– PS shut-down
– Extract stored energy into an external circuit (**dump resistor** or coupled inductance)

$$V_{max} = I_0 R_D$$

R_D chosen to have

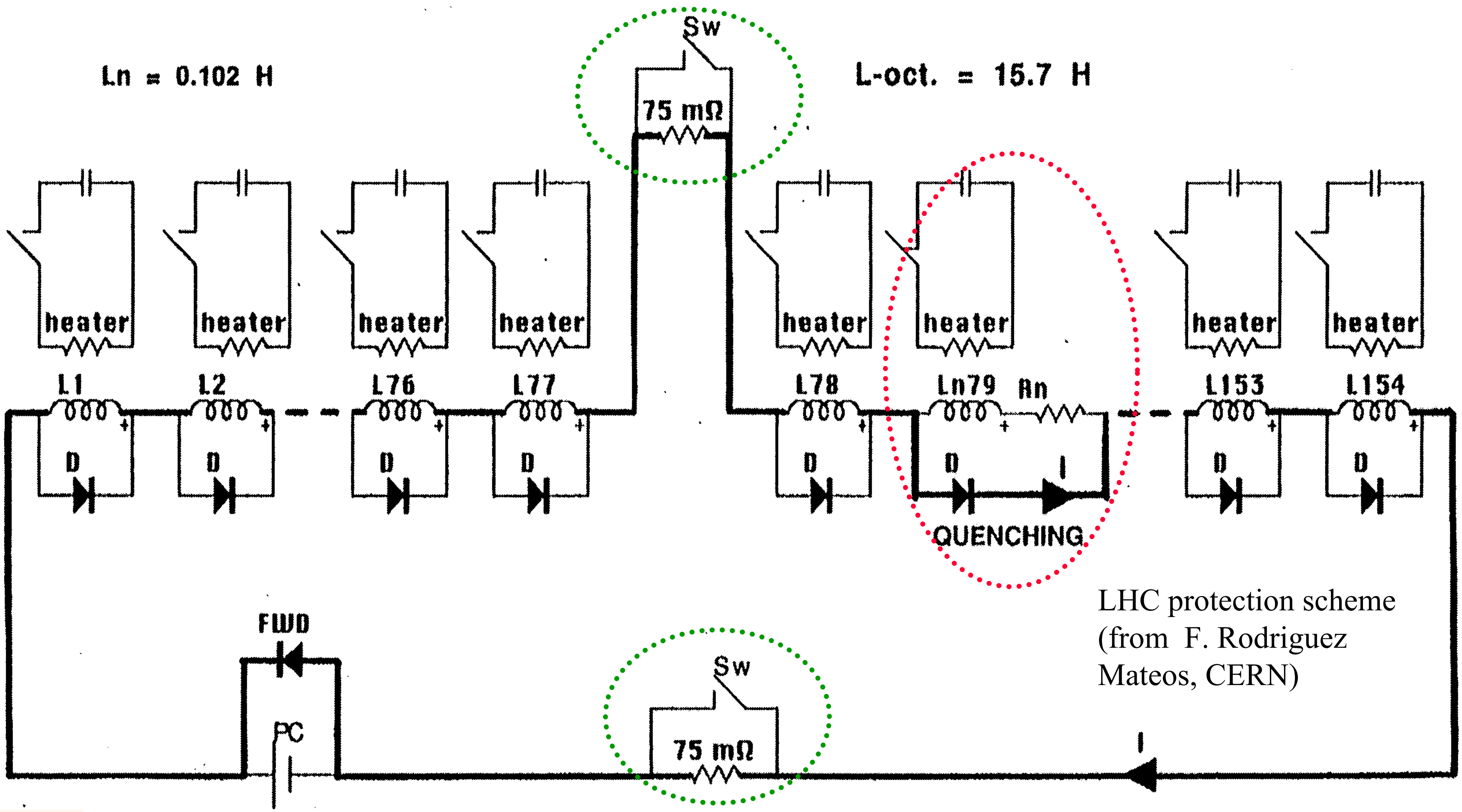
V_{max}< 1 kV =>

R_D is fixed with the current, cannot be increased with magnet size.



13 kA current breaker for LHC

Quench protection in a string



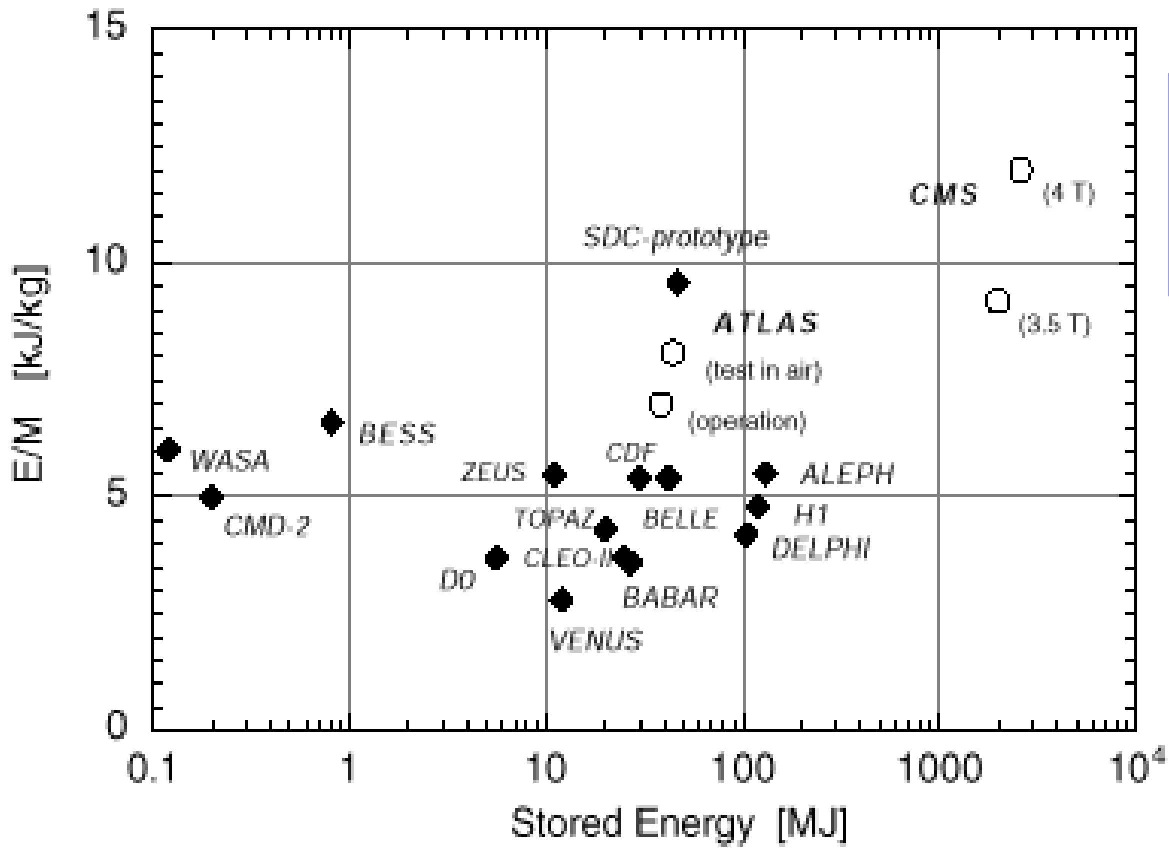
LHC protection scheme (from F. Rodriguez Mateos, CERN)

external thyristors or cold diodes to bypass the quenching magnet

⇒ Two current circuit: **1- Magnet string + dump resistors** (τ ~100 s)

2- Quenched magnet + diode (τ ~ 0.1 s)

4- Spread energy into the winding



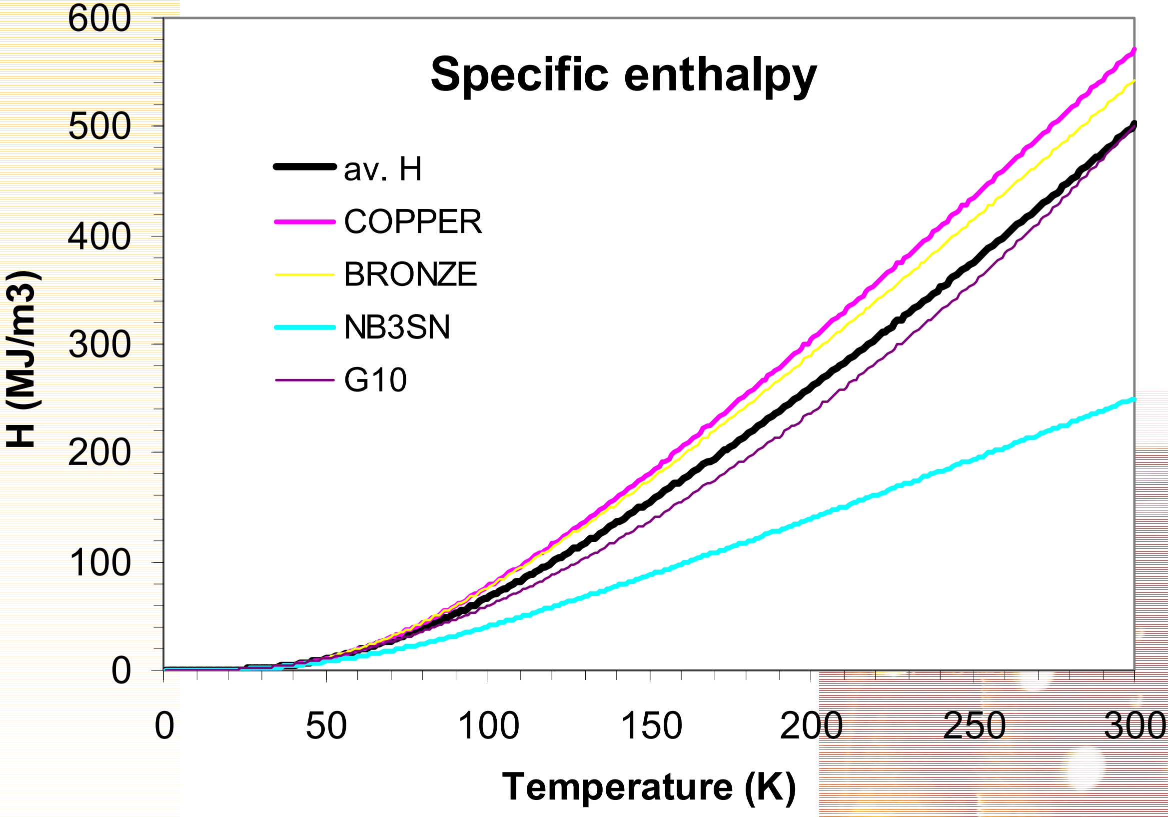
Detector energy densities

(well stabilized)

- Natural **quench propagation** – for small magnets
- **Quench heaters**
- Use of **quench-back** (quench induced by fast current decay)

4- Spread energy into the winding

Example :

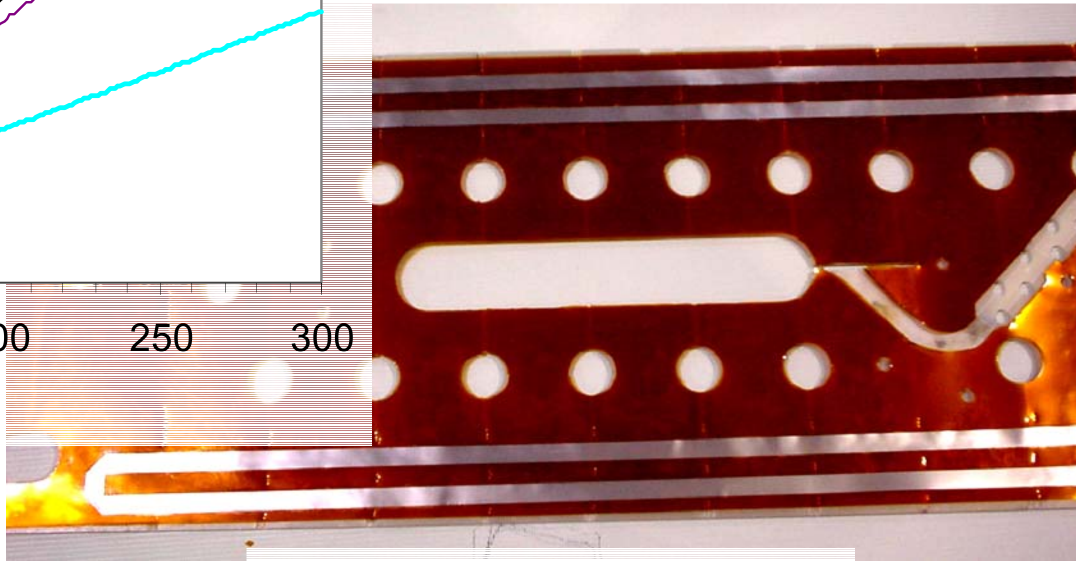


VLHC–CC:

E/M ~ 20 kJ/kg

$\Rightarrow$ E/V = 120 MJ/m^3

$\Rightarrow T_{MAX} = 130$ K ($=T_{BULK}$)



Racetrack #2 quench heater

Hot Spot temperature - MIIts

Adiabatic equation => conservative peak temperature estimation

(No heat exchange with Helium ; No heat conduction)

per unit volume

Joule heating

$$\rho(T)\ J(t)^2\, dt = c_P(T)\, dT$$

Temperature rise

Current decay =>

$$\boxed{QI(T_{peak}) = \int_0^{\infty} I^2(t)\, dt = A^2 \int_{To}^{Tpeak} \frac{c_P(T)}{\rho(T)}\, dT}$$

<= Material properties

Definition...

The MIIts value is the square current integrated in time.

MIIts – current decay

$$QI(T_{peak}) = \int_0^{\infty} I^2(t)\,dt = I_o^{\,2}\tau_d + \int_{\tau_d}^{\infty} I^2(t)dt$$

τ_d = delay time = quench detection time +
+ quench heaters activation time

After the delay time the current decays:

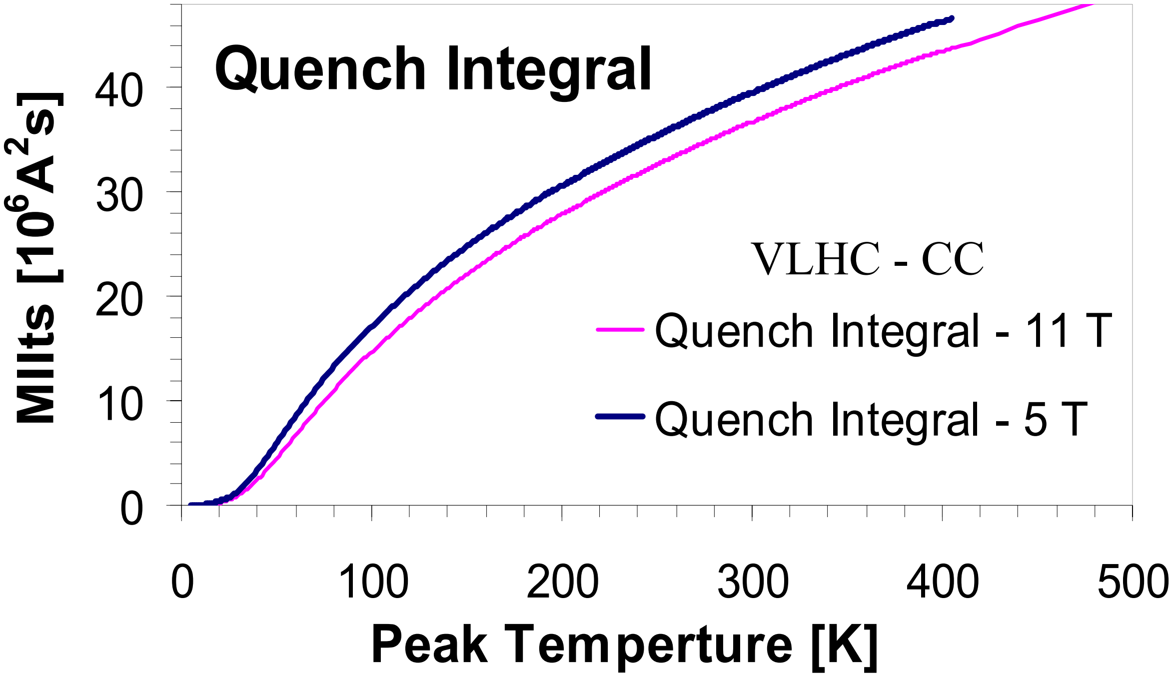
- External dump resistor R_D:

$$\mathbf{I=I_o e^{-t/\tau}\ ,\ \tau=L/R_D}$$

- With heaters: R=R(T): depends on the normal zone volume, temperature and field.

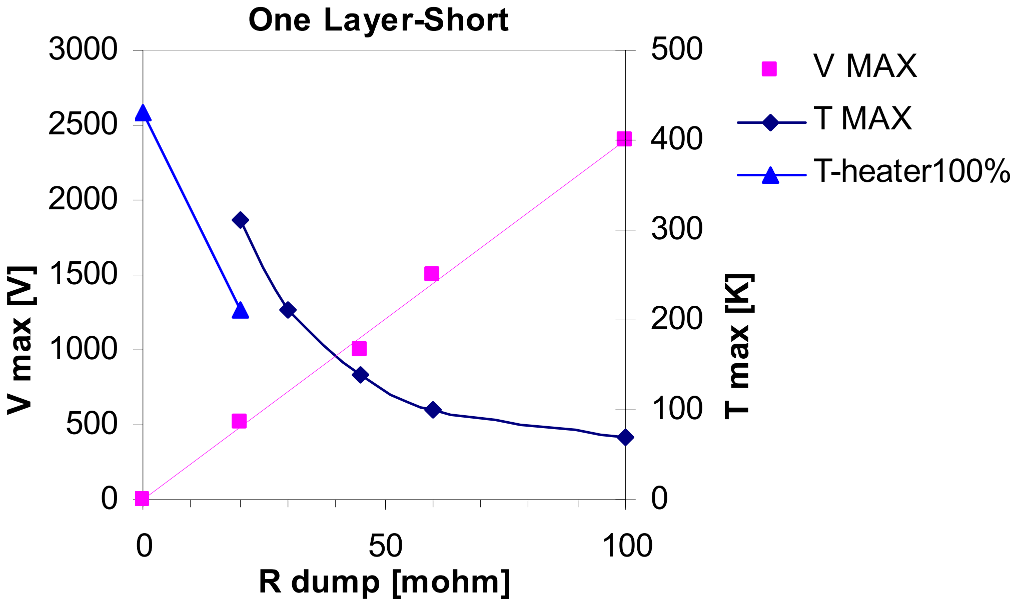
How can we reduce the peak temperature?

- **Decrease J**
  (larger cable, more copper)
- **Fast current ramp down**
  (early quench detection, fast and effective heater action)

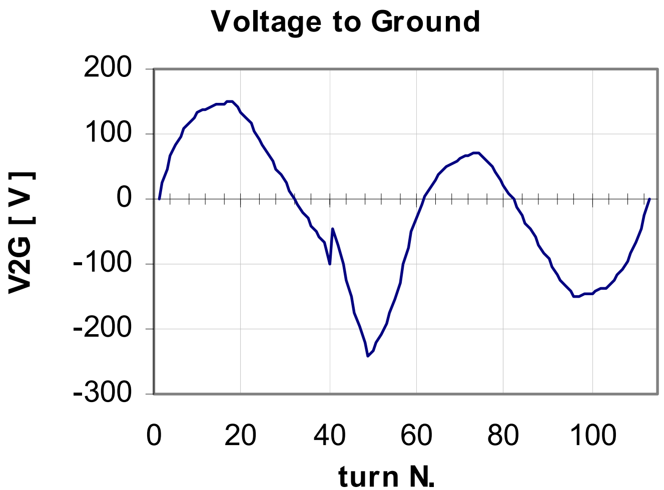


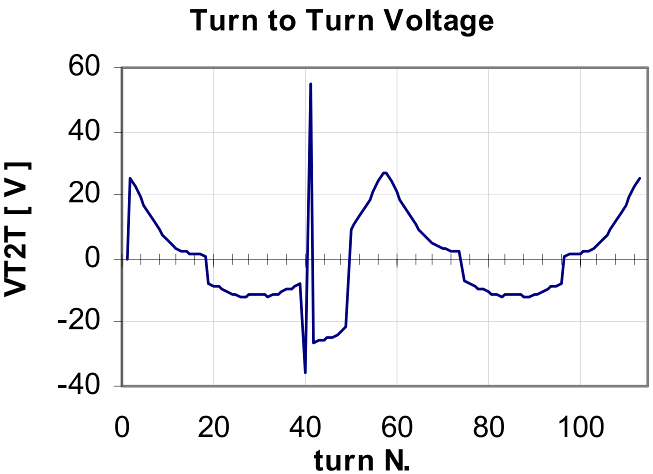
Voltage

- External dump resistor:
  $V_{max} = I_0 R_D$
  $V_{max} < 1\text{-}2\ kV$



- No dump:
  - $V_{tot}=0$ (Resistive and inductive voltages compensate over the magnet)
  - High turn to turn voltage between the hot spot and cold zones

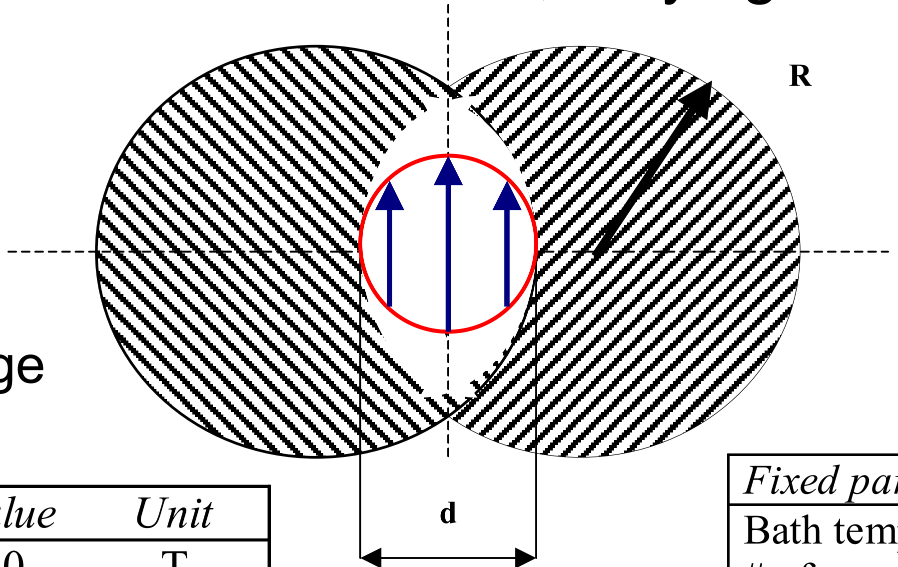




Generic HFM quench study

An analytical calculation of trends, varying

- bore field
- aperture size
- Current
- J_c of Nb_3Sn
- J_{CU}
- Heater coverage

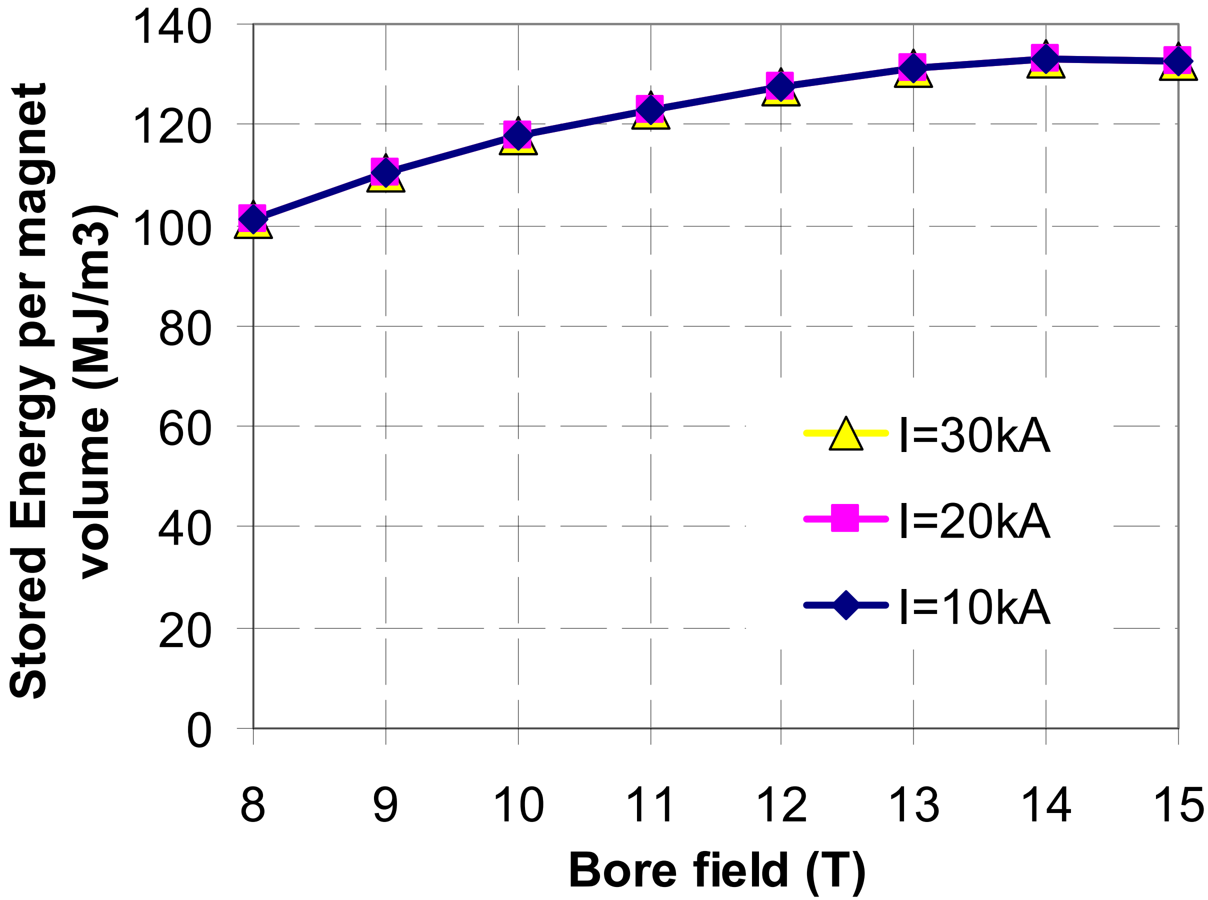


... *when fixed*	*Value*	*Unit*
Bore field	10	T
Oper. current	20	kA
Total delay time	30	ms
Bore diameter	40	mm
J_{CU}	2	kA/mm^2
J_c at 12 T	3	kA/mm^2
Magnet length	15	m
Heater coverage	50	% area

Fixed parameters	*Value*	*Unit*
Bath temperature	4.5	K
# of apertures	2	
Bronze in SC	25	%
Insulation in cable	25	%
copper RRR	50	
Peak / bore field	1.2	
I_C degradation	10	%
Operating margin	85	%
τ correction factor	1.2	
Quench velocity	1	m/s

Stored energy density

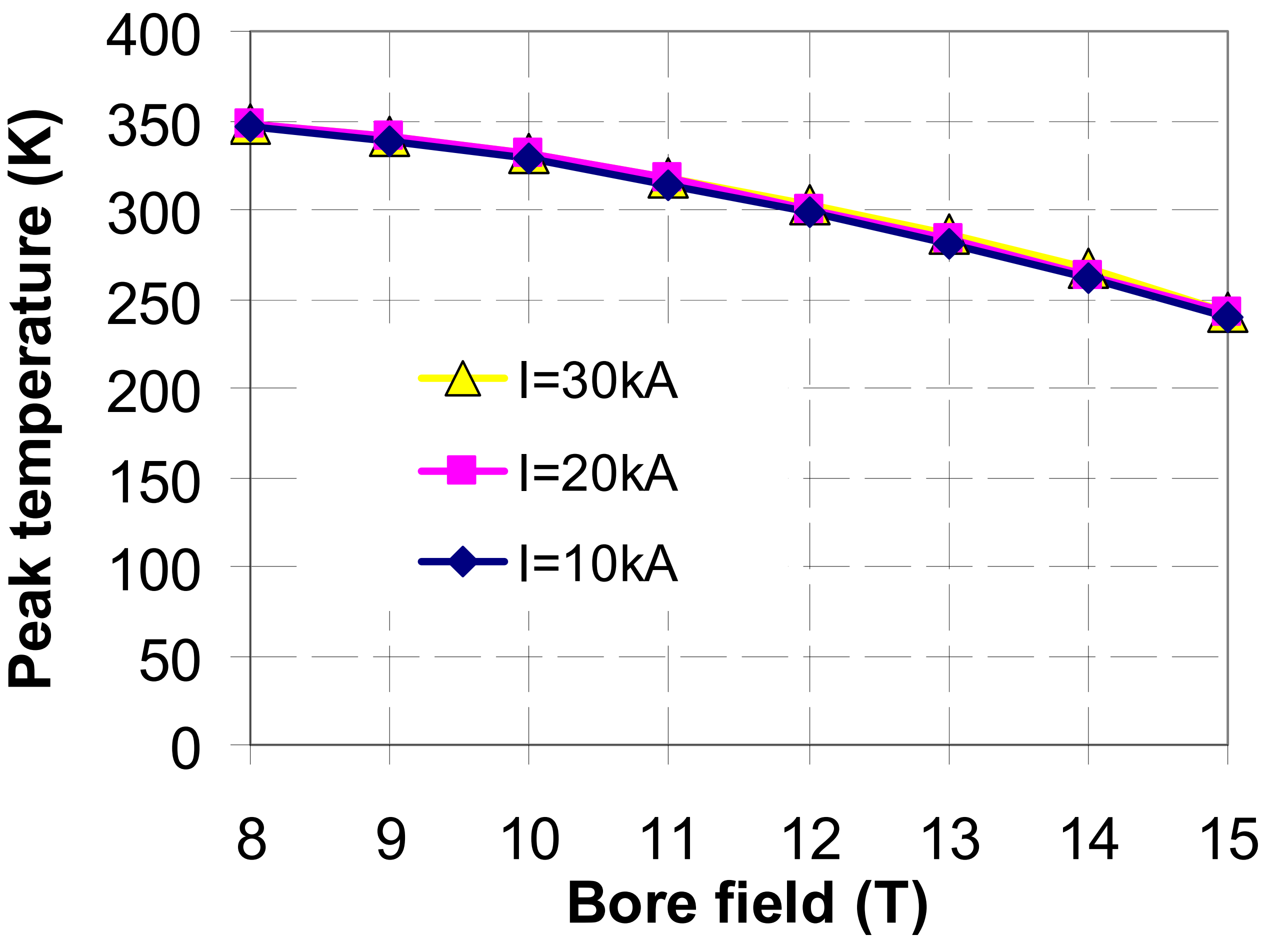
Increasing the field and keeping all the other parameters fixed (I, J_{CU},…)



→ Increase number of turns and cable size

→ Increase both total stored energy and coil volume

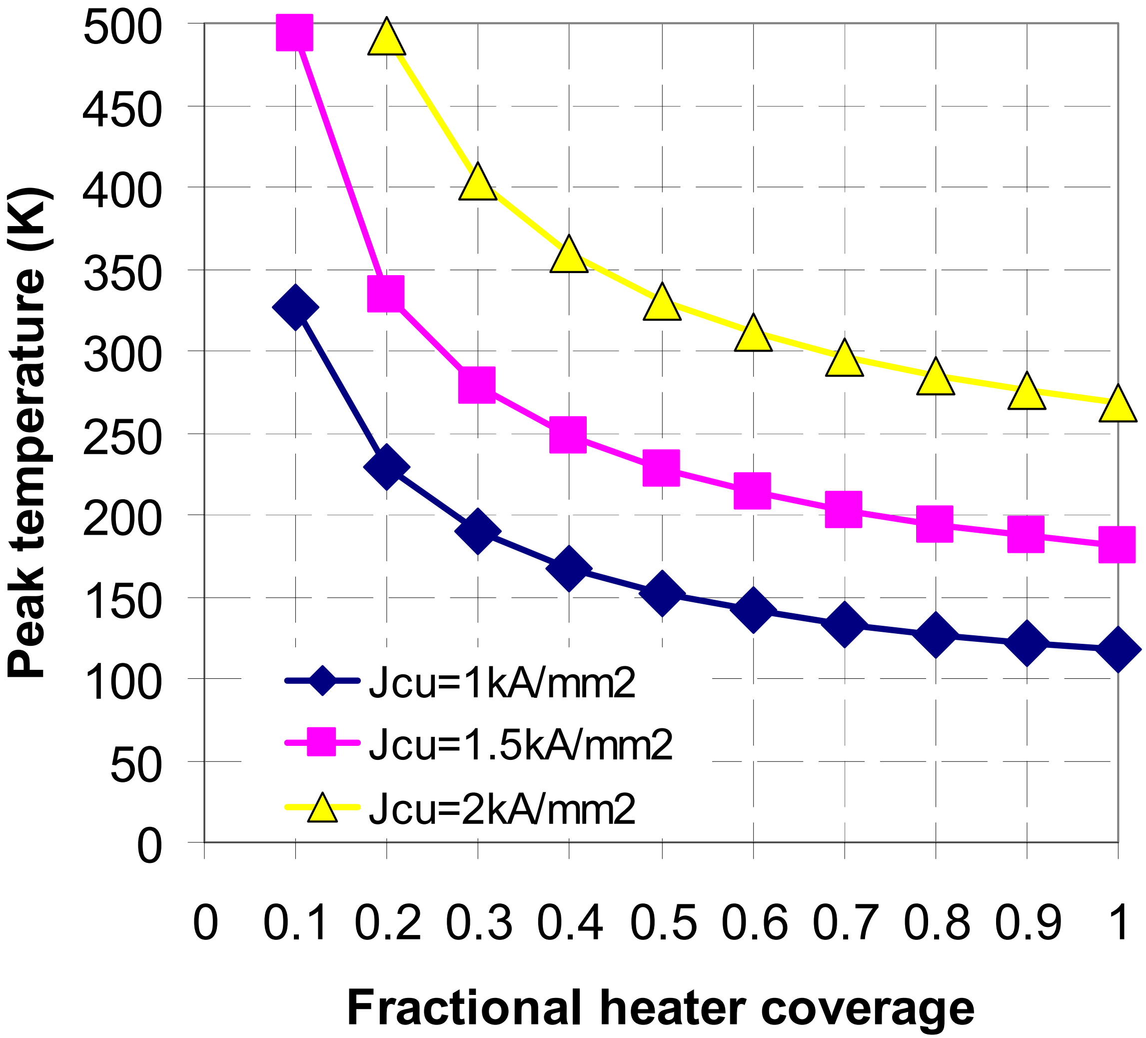
Peak temperature vs. field



1- Tpeak does NOT depend on the current

2- Tpeak does NOT increase with field

Peak temperature vs. J_{CU} and heaters



- J_{CU} is the parameter with the largest impact on quench protection.
- The drop of T_{peak} with increased heater coverage is sharp for low HC.

Quench simulation programs

QLASA - developed by L. Rossi, et al. at INFN-LASA

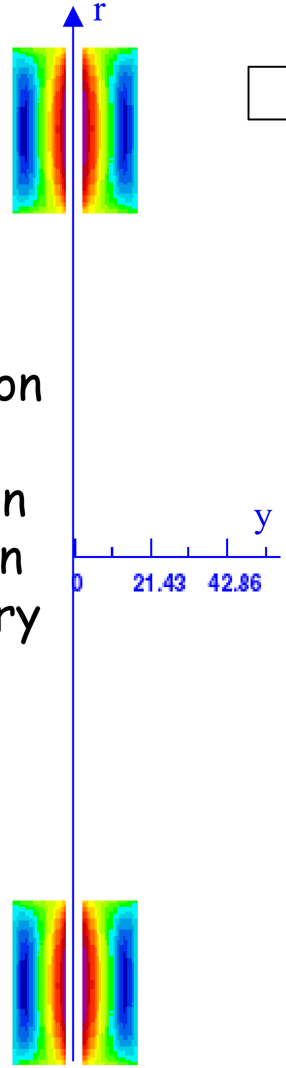
- t=0 : "spontaneous" quench
- t=dt : normal zone propagation: ellipsoid
- t+dt : new layer & update of inner layers: Vol,T,R => update of total R, I, V

Quenchpro - developed by P. Bauer at Fermilab

- simpler program (using a uniform temperature in the coils and uniform field)
- calculates the turn to turn inductance matrix, on the basis of the coordinates of all turns, to derive the turn to ground and turn to turn voltages.

Both based on the adiabatic heat balance equation, the programs calculate peak temperatures in agreement to within ±10%.

Quench simulation with QLASA

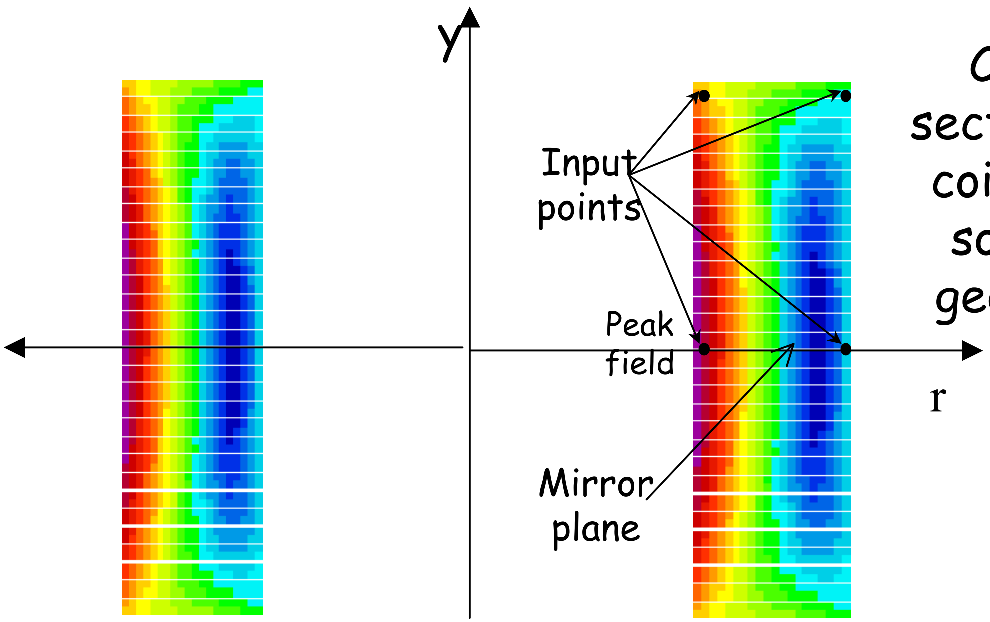


Cross-section of the racetrack in the common coil geometry

Racetracks ⇒ solenoids

same cross section

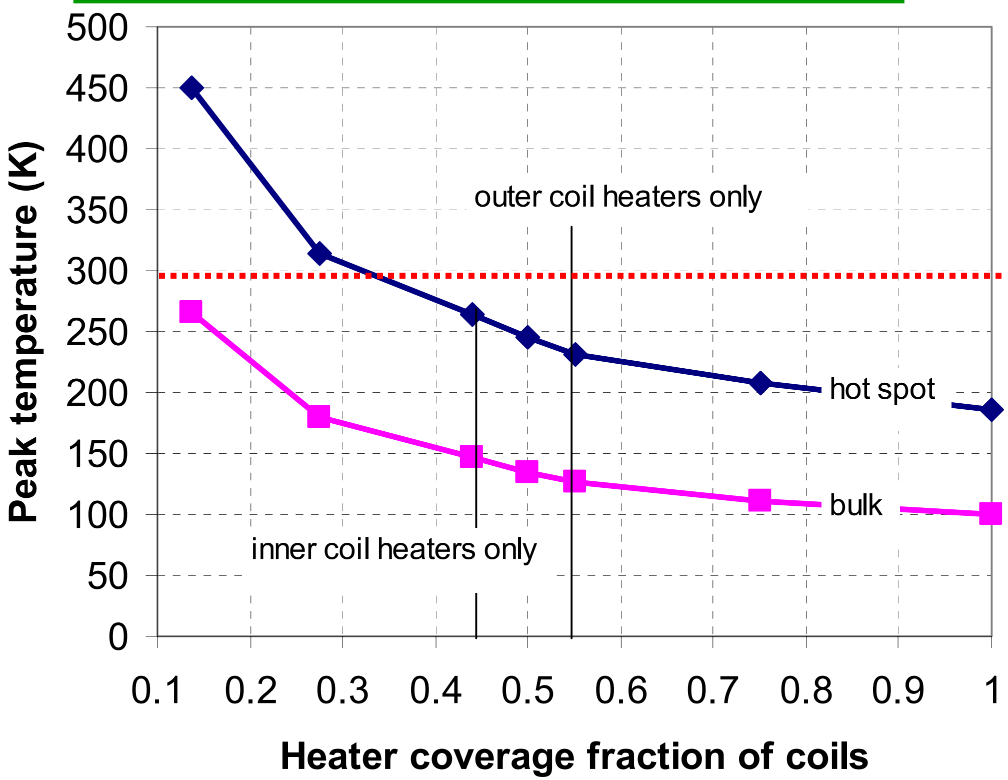
same volume

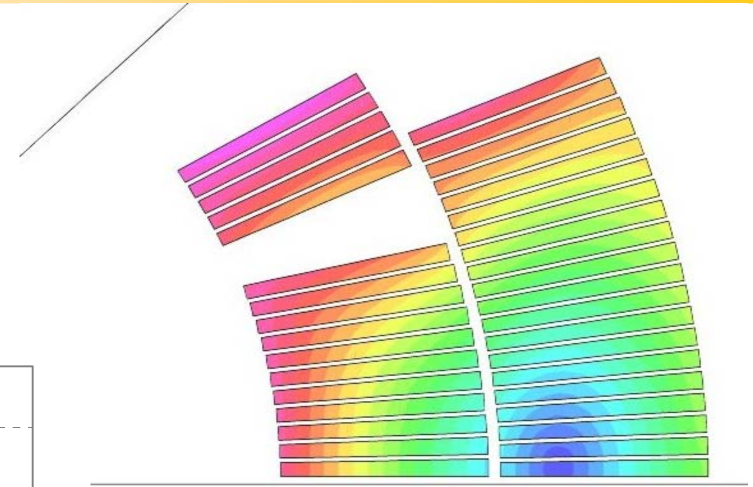


Cross-section of 1 coil in the solenoid geometry

HGQ-2

Parameters	HGQ-2	MQXB	
Aperture	90	70	mm
Gradient	210	205	T/m
Current	14.5	11.3	kA
I max	16.5	-	kA
Inductance	4.7	3.5	mH/m
Stored energy	489	225	kJ/m



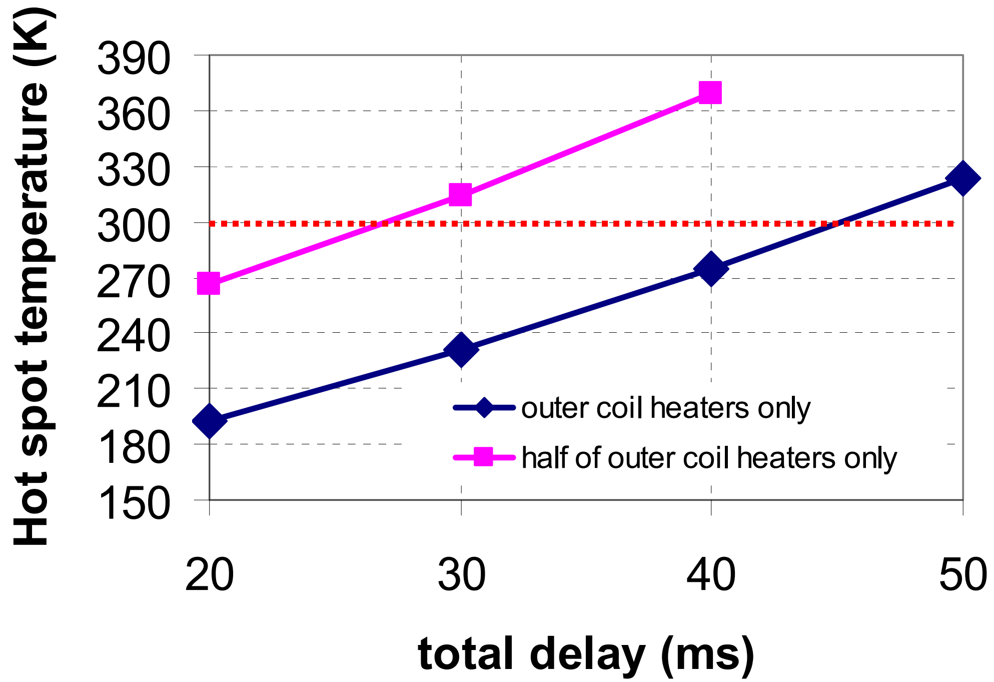


Peak field = 10.25 T

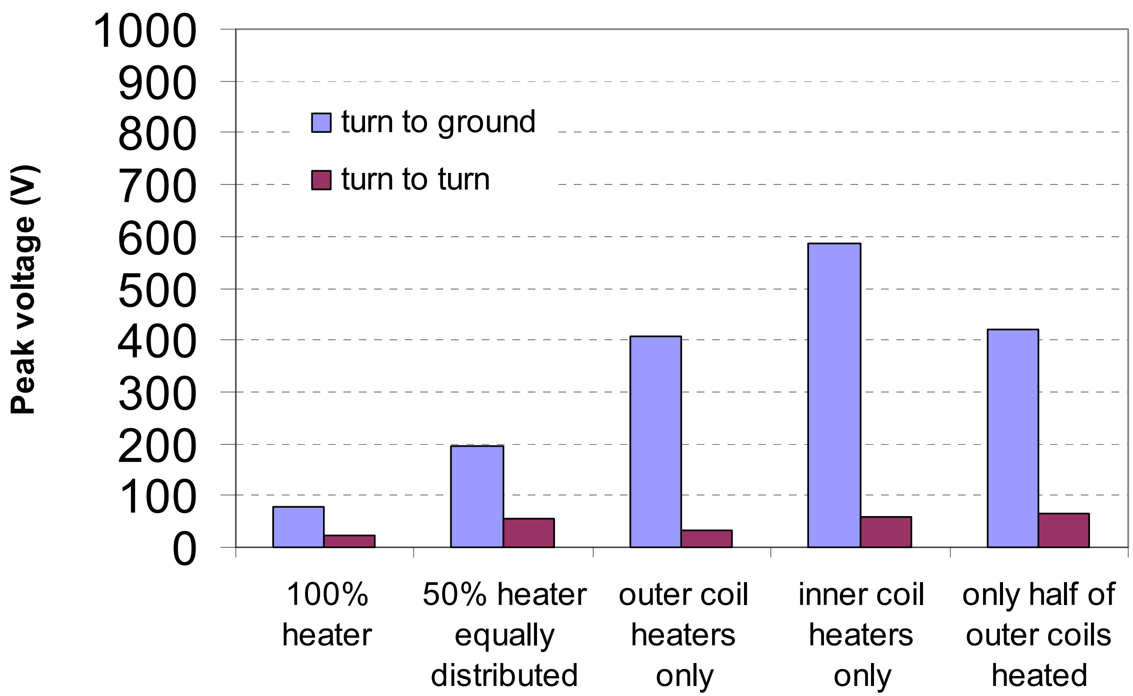
Cable parameters		
N. of strands	42	
Strand diam.	0.7	mm
Insulation thick.	0.18	mm
Cu/NCu ratio	1.2	
RRR	50	
J_{CU}	1645	A/mm^2
Cross-section	24.3	mm^2

HGQ-2

Heater parameters	25% coverage	50% coverage	
Heater systems (+ redundancy)	2+2	4+4	
Capacitors per heater PS	3	3	
Capacitance per capacitor	4.7	4.7	mF
Operating V / maximum V	350/500	350/500	V
Peak heater power per surface	38	38	W/cm^2
Peak current	150	150	A
Number of strips per system	4	4	
Cu cladding	1:3	1:3	



HGQ-2



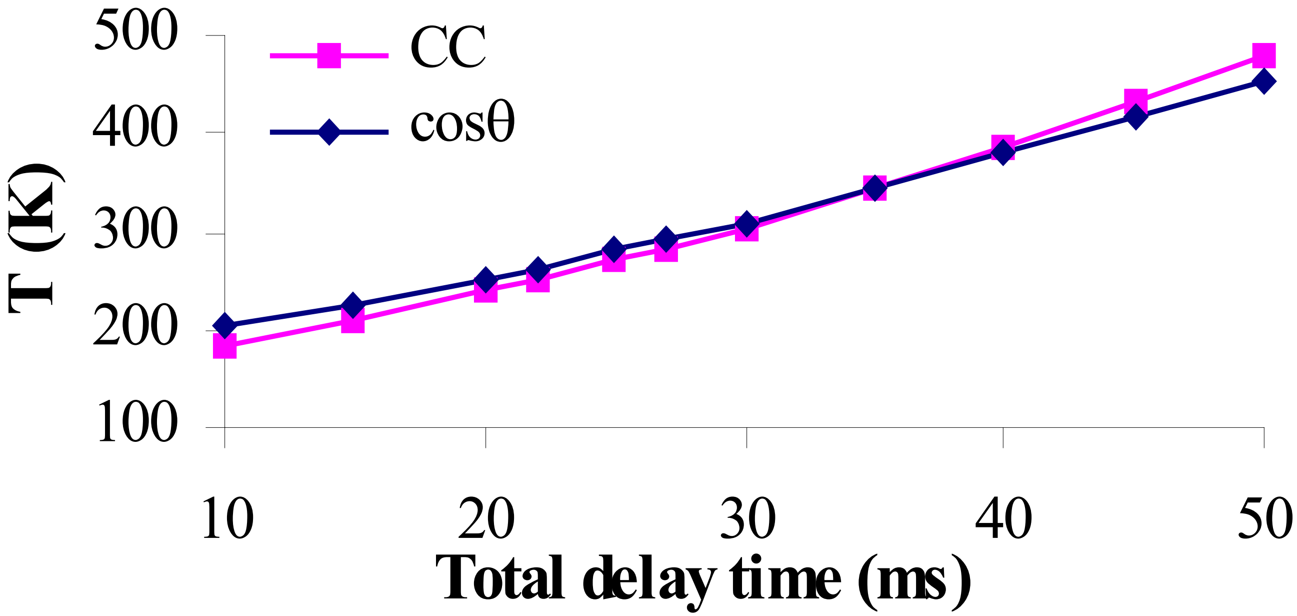
	2x25% coverage	2x50% coverage	
Heater delay	5+25	5+25	ms
N. of heaters	2+2	4+4	
Max. hot spot T	231	186	K
Max. bulk T	127	100	K
Max turn-to-ground V	407	78	V
Max. turn-to-turn V	30	22	V

Parametric quench studies

To find the conductor and quench-heater requirements to limit the peak temperature and the voltages in the coil during a quench

Peak temperature vs. total delay time

HC=50/100%, RRR=50, Cu/NCu=1.2/1.0 (cosθ /CC)



Set temperature limit: 400 K

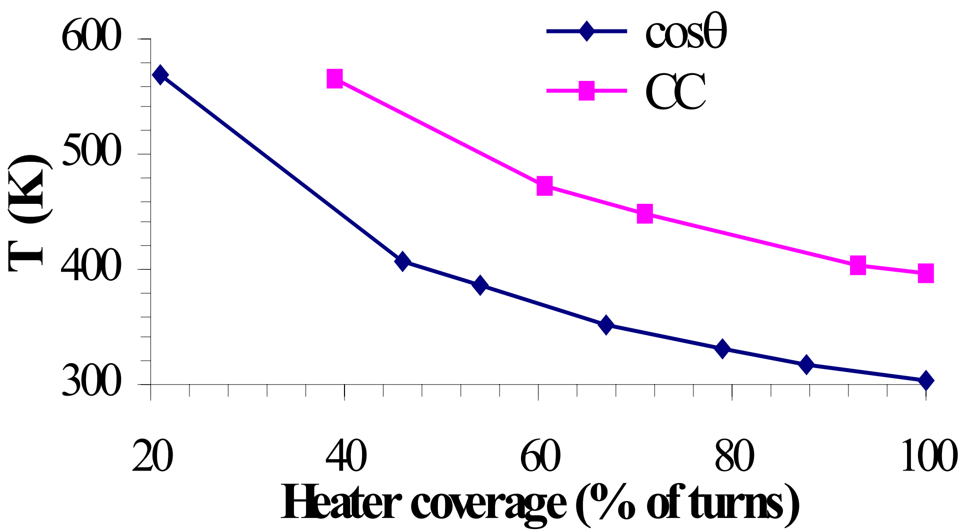
Requirement: τ_H < 40 ms

Parametric quench studies

Heater coverage:

Fixed parameters: t_H=40 ms, RRR=50, Cu/NCu=1.2/1.0 (cosθ/CC)

Peak Temperature



Requirements: Heaters=50/100% cosθ/CC

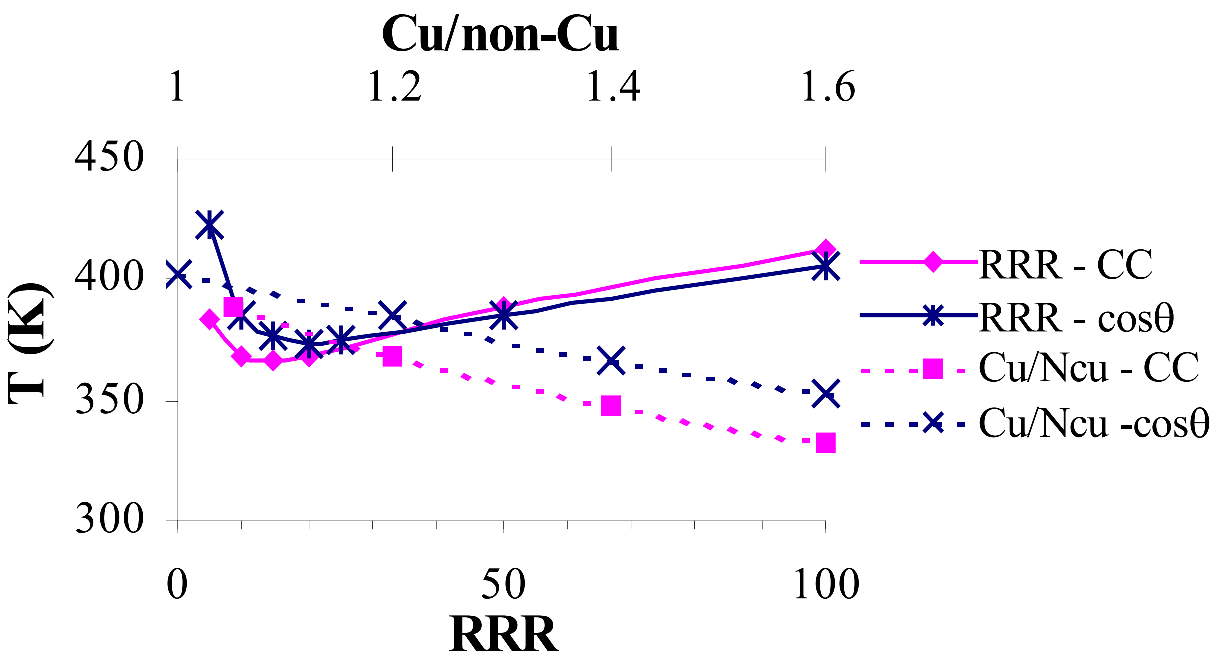
Peak V to ground

	V (kV)	Heater position	turn %
cosθ	0.30	all 48 turns	100
	0.91	outer layer only	54
	1.36	inner layer only	46
CC	0.24	all 52 turns	100
	0.98	36 mid-plane turns	71
	1.87	18 mid-plane turns	35

The voltages depend not only on the heater coverage %, but also on the position of the heaters.

Parametric quench studies

T peak vs. RRR (Cu/NCu=1.2/1) **and copper content** (RRR=50)
t_H=40 ms, HC=50/100% (cosθ /CC)



Opposite effects of resistance (R):

1- the lower R the lower the heat generation at the hot spot;

2- the lower R the longer the decay time, which ultimately raises the peak T.

$$\left.\begin{array}{l}\text{Tpeak} < 400\text{ K}\\ \text{V} < 1\text{ kV}\end{array}\right\} \Rightarrow \left\{\begin{array}{l}\text{Cu/NCu} > 1\\ \text{RRR} \sim 10-70\end{array}\right.$$

Thermal stress study

- Cable tests:

  To measure the critical current degradation directly as a function of peak temperature during a quench

- Magnet quench test
  - Quench parameters (quench velocities, heater efficiency…)
  - Degradation with peak temperature

- Quench simulation with FE stress analysis

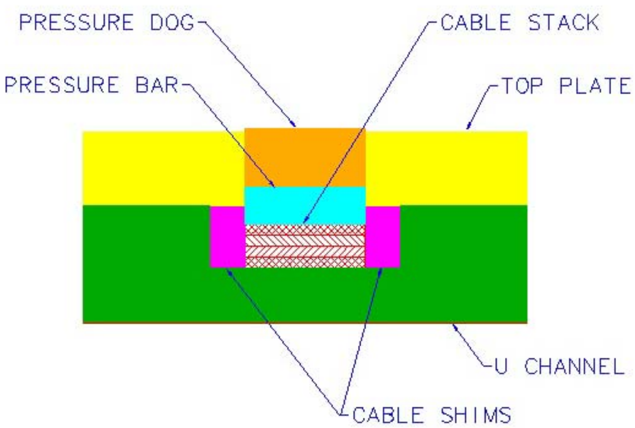
Nb_3Sn cable quench test

Main goal : Study of Nb_3Sn degradation as function of peak temperature

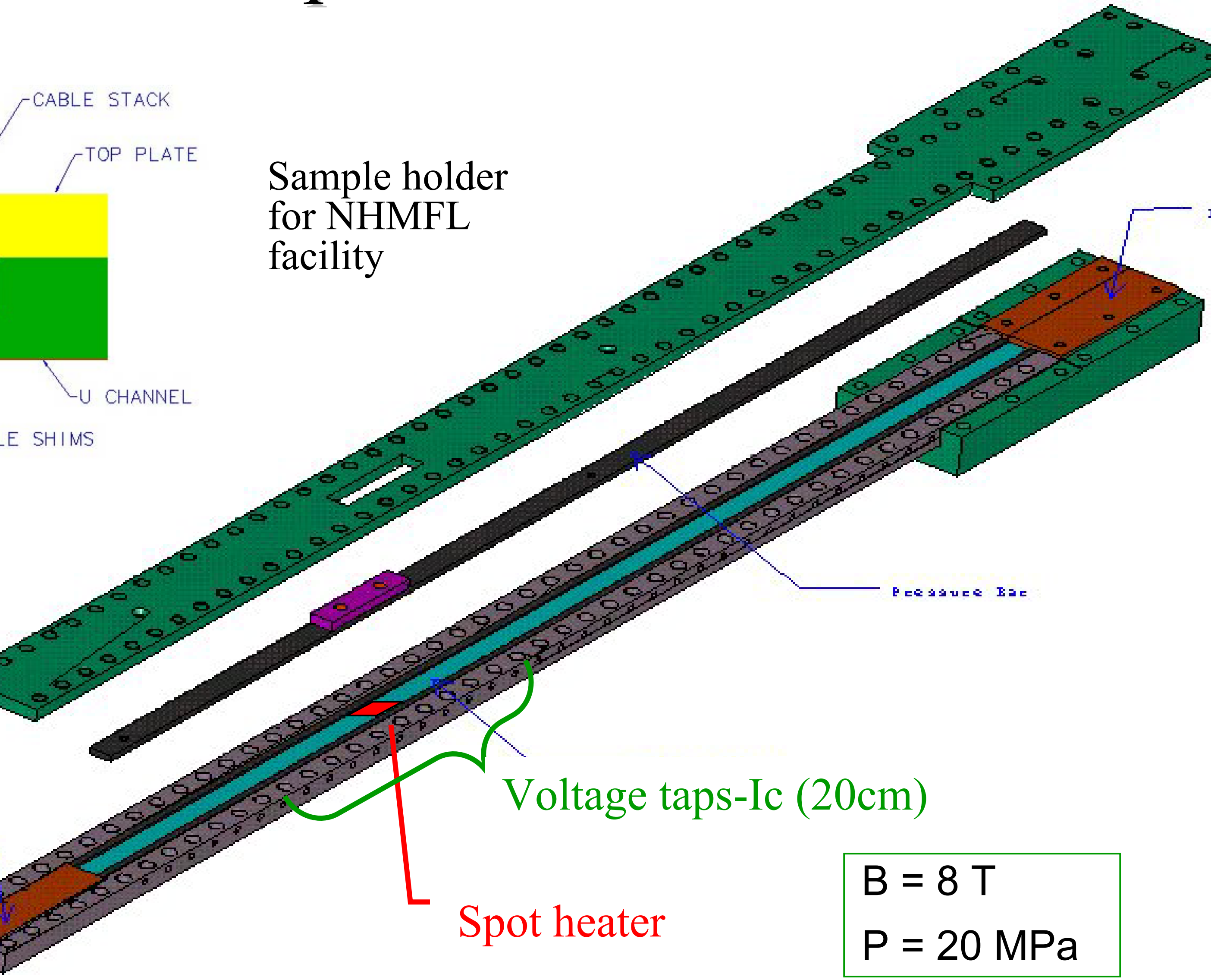
Experiment concept :

- Induce quench with a spot heater
- High current for a chosen delay time
- Temperature rise
- Cold magnet environment (or sample holder) $\Rightarrow$ strain
- measure I_C and repeat till I_C degradation

Experiment set up



Sample holder for NHMFL facility



B = 8 T

P = 20 MPa

Thermal stress

- Intrinsic pre-compression* : 0.28 % ;
- Irreversible tensile intrinsic strain* : 0.4%
- Pre-strain at 400 K of 0.15 %,
- Uni-axial longitudinal stress for constrained cable, fixed ends

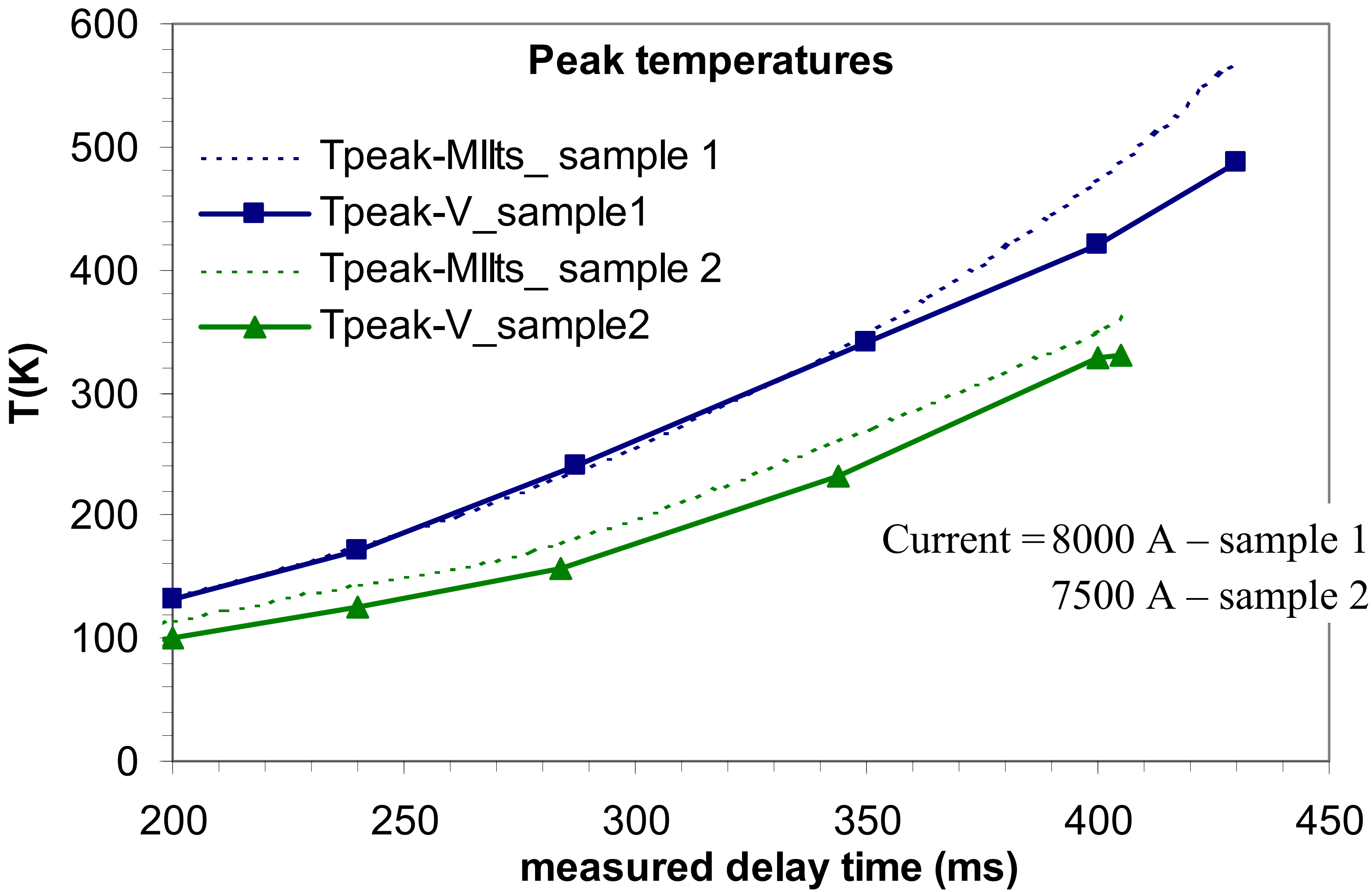
$$\varepsilon(T_{peak}) = \frac{c}{2} \cdot (T_{peak} - T_{bath})$$

=> **ε(400K) = 0.175%**

=> **total intrinsic strain ~ 0.3% compressive**

* Ekin, Private com., HP1-ITER IGC strand measured at MIT, 10/01.

Test results



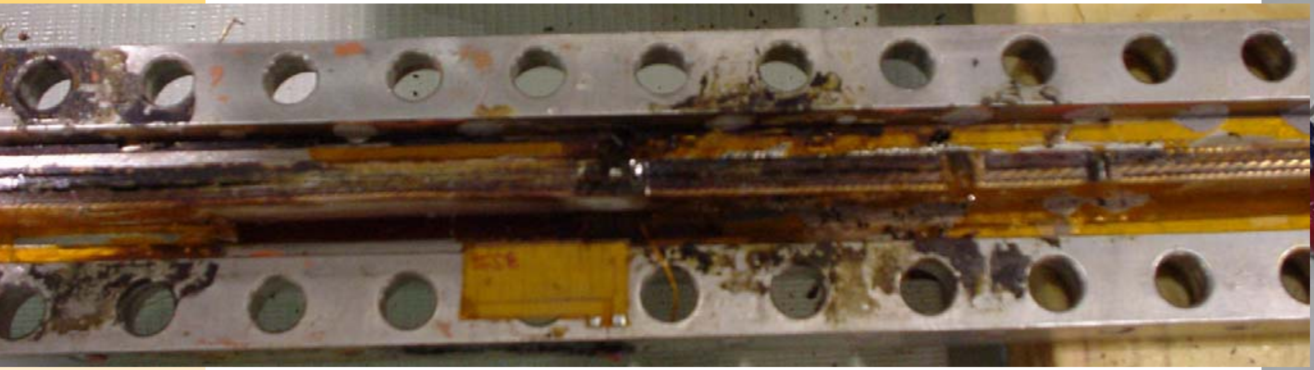
Summary of test results

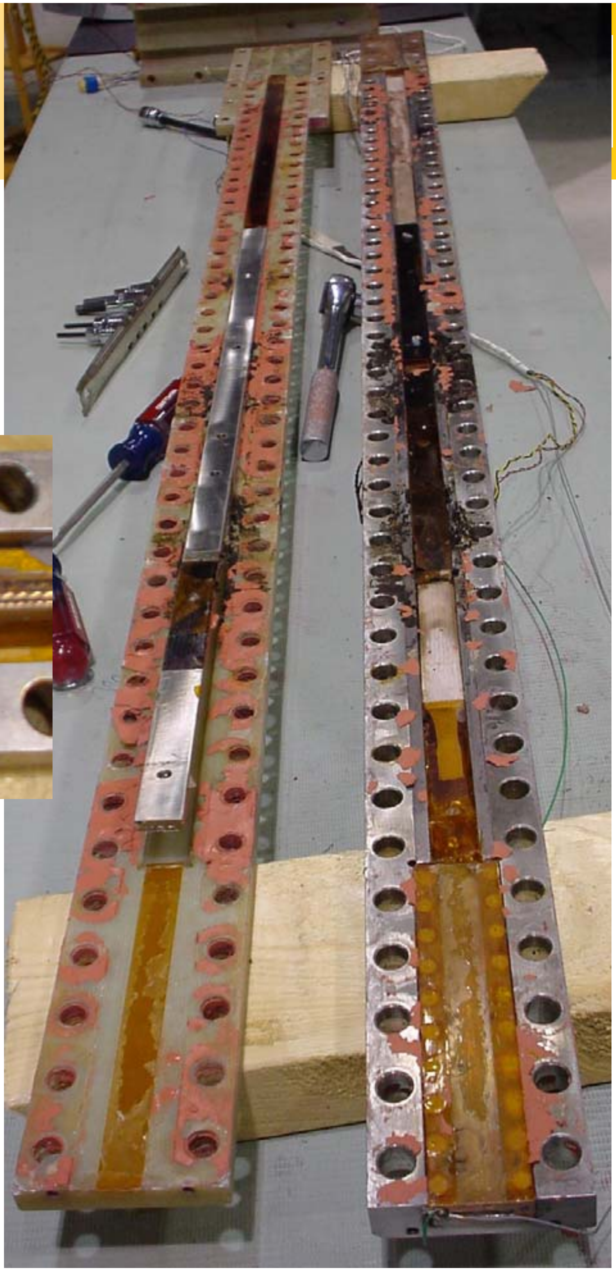
- No degradation up to ~ **420 K** (straight sample)
- No degradation up to ~ **350 K** (bent sample)
- MIIts calculations with only Copper and ~15 % overestimation
- Turn to turn propagation time ~20 ms

Next developments
- Temperature sensors
- Strain gages
- FE model

Temperature !

burned epoxy





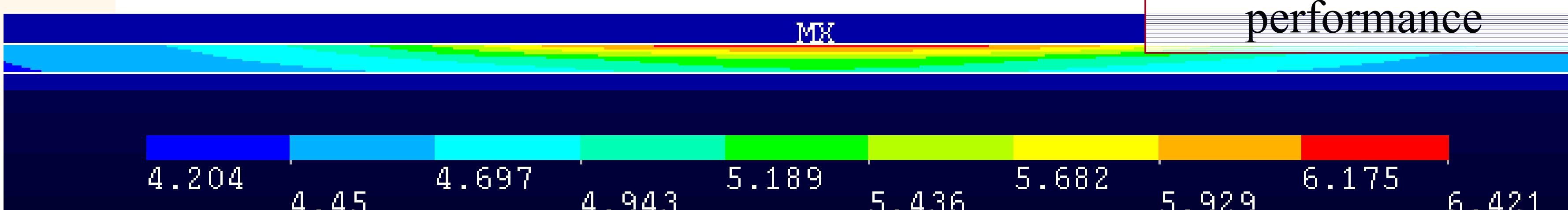
Simulation and FE stress analysis

- GOAL: Thermo-mechanical analysis of the stress during the quench
- METHOD:
  - FE model of the magnet :

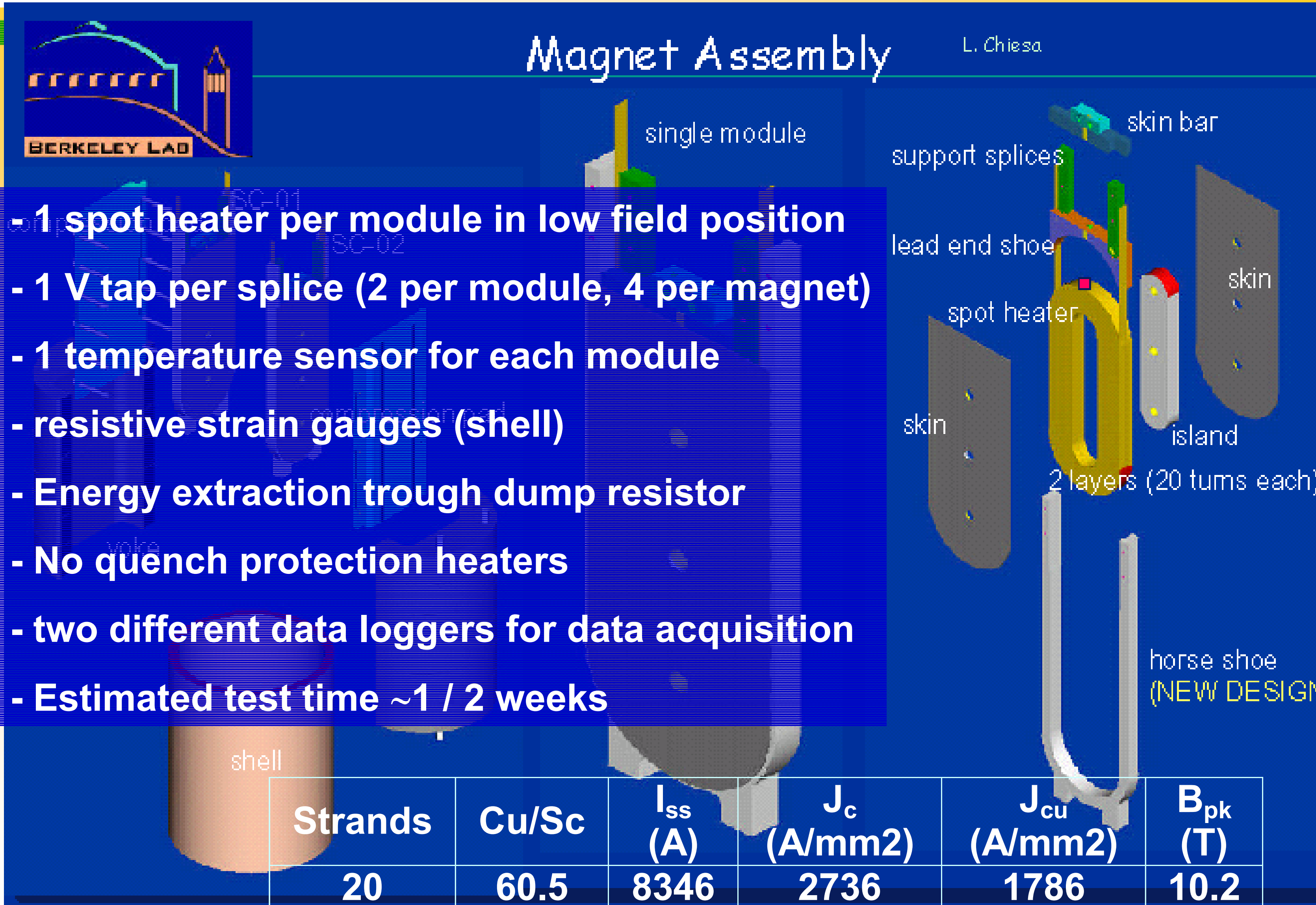
  detailed, must represent the conductor and the insulation

  - Detailed temperature distribution
  - Simulation of the quench
    - FE simulation
    - External code

Stress concentration in the epoxy can cause cracks that might eventually degrade the magnet performance



Quench tests at LBL



- 1 spot heater per module in low field position
- 1 V tap per splice (2 per module, 4 per magnet)
- 1 temperature sensor for each module
- resistive strain gauges (shell)
- Energy extraction trough dump resistor
- No quench protection heaters
- two different data loggers for data acquisition
- Estimated test time ~1 / 2 weeks

Strands	Cu/Sc	I_{ss} (A)	J_c (A/mm2)	J_{cu} (A/mm2)	B_{pk} (T)
20	60.5	8346	2736	1786	10.2

Summary

- The large stored energies and current densities of the high field Nb_3Sn magnets, can cause high peak temperatures during the quench.
- Rapid thermal expansion of conductor during the quench can result in permanent critical current degradation.
- It is necessary to define the maximum temperatures that can be accepted in the coils during a quench.
  - Experimentally: cable quench tests and racetrack
  - Theoretically: quench simulation and FE model